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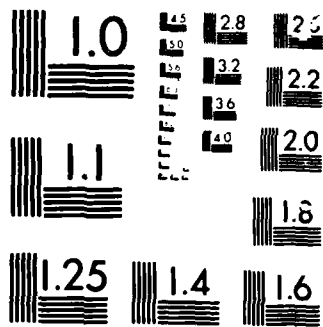
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Current German Laser and Quantum Optics
Research Reviewed at the 50th Annual Meeting
of the Physikalische Gesellschaft

Paul Roman

April 23, 1986

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CURRENT GERMAN LASER AND QUANTUM OPTICS
RESEARCH REVIEWED AT THE 50th ANNUAL
MEETING OF THE PHYSIKALISCHE GESELL-
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1 INTRODUCTION

The quantum optics division of the (West) German Physical Society, in cooperation with the German Society for Applied Optics, held its major annual meeting within the larger framework of the 50th Annual Meeting of the Society. The convention took place 17 through 21 March 1986 in the university city of Heidelberg. The organizer and general chairman of the meeting was Professor Dr. H.J. Eichler, Institute of Optics, Technical University, Berlin. There were about 210 participants; a total of 107 talks were given. The participants and speakers were almost all West Germans; the presentations were given in German, and the abstracts (which I will supply on request) are also written in German. There were no representatives from East Germany or any other Communist countries, except for a visiting lady scientist from China, who read a paper on work done here at Braunschweig.

The agenda of the quantum optics meetings consisted of four plenary overviews and principal lectures (timed so as not to conflict with any other divisional session meetings). The rest of the talks were held in small divisional sessions.

The divisional sessions were titled as follows:

- Ultrafast and coherent spectroscopy (two sessions)
- Integrated optics and optical fibers
- Semiconductor lasers
- Frequency multiplication and phonon interactions
- Phase conjugation and photorefractive effects
- General laser spectroscopy
- Photochemistry and photobiology
- Dye lasers and frequency stabilization
- Optical bistability and optical computers

- Solid-state lasers (two sessions)
- Optical chaos and photon statistics
- Industrial reports and miscellaneous

2 SOME PRESENTATIONS

Plenary Sessions

Among the plenary talks, I will report on two. The first, by F.P. Schäfer (Max Planck Institute for Biophysical Chemistry, Göttingen), dealt with the production of ultrashort laser pulses in the UV and VUV region. After a general review of this relatively new field, he gave a fascinating description of his own method, which is based on a complicated chain of dye amplifier cells, where, at a crucial point, a distributed feedback dye laser (using a holographic grating) is inserted. The whole system is driven by a single excimer laser, and no complicated synchronizing electronics is needed. Subsequently Schäfer discussed various possible x-ray lasers where, by the nature of the mechanisms used, the pulse-length is expected to be very short to start with. As an alternative to the Livermore's Se^{24+} -based scheme, he revived an older idea which also used plasma-columns but where the basic physical process is inner shell ionization. Efficient amplified stimulated emission could be achieved, Schäfer suggested, by a clever arrangement, which he described in some detail. He also calculated that this methodology would lead to pulses with lengths of only 1/10 or less of a femtosecond.

The second plenary talk that I found unusually exciting, was delivered by H. Walther (Max Planck Institute for Quantum Optics, Garching) who discussed his and his associates' successes in constructing a single-atom maser. The experiments are based on the fact that Rydberg atoms with high principal quantum number (60 or more) permit the occurrence of stimulated emission amplification if, in a superconducting and extremely cold (2°K) resonator (with ultrahigh vacuum in its cavity), only a single atom is introduced at a time. In this device one can study quite easily the interaction of a resonator mode with

the single atom. Temporal observation of the atoms permits the study of the statistics obeyed by single microwave photons. The measurements clearly indicate that a "squeezed state" (with minimal amplitude fluctuation) has been achieved. Furthermore, remarkable quantum-electrodynamical effects, such as the vacuum point energy and vacuum point fluctuations, as well as the resonator's effect on the Lamb shift, can be experimentally studied. Incidentally, looking at the device as a bona fide maser, it runs at 10^{-20} -W output--the lowest possible value. Of course, the cm-wavelength radiation cannot be coupled out from the cavity because it would spoil the extremely high Q-value needed for prolonged operations. Nevertheless, it may not be idle thinking to hope that, in some modification, we may have here a minimal-noise, maximally coherent frequency standard.

Divisional Presentations

The divisional presentations consisted of a few special reports (30 minutes long) and nearly 100 short papers (15 minutes long). These presentations were given in two parallel sessions. For this reason, and also because of my current interests, the topics I have chosen to report on do not imply a value judgment either on the areas or on talks of particular speakers I omit mentioning.

The following subject areas will be covered:

- Gas lasers
- Integrated optics
- Nonlinear optical processes
- Solid-state lasers

Gas Lasers

G. Merkle (Plasma Research Institute, Stuttgart University) reported on work aimed at our better understanding of lasers that are based on an "inverted V" three-level system and where a strong traveling pump-wave and a strong standing-wave laser field is present. A Stuttgart-Barcelona cooperation worked out many details of the theory and predicted interesting multiple-photon ef-

fects. Merkle now used a 2-m-long methanol FIR laser (pumped by a CW-operated CO₂ laser) to experimentally verify these effects. Indeed, he found that for transitions which are both homogeneously and Doppler-broadened, resonant pumping gives strong amplification in the direction of the pump beam, but not so in the opposite direction, where, in fact, even absorption may be seen. The effect is a consequence of a coherent interaction between the forward- and backward-running laser fields.

An interesting contribution by B. Rückle and associates (Lambda Physik, Göttingen) reported on tunability studies (at the bands of 193, 248, and 308 nm) of systems consisting of a tunable excimer oscillator and a regenerative, unstable oscillator excimer amplifier. Frequency selection was achieved by a grating and an additional etalon. If only the grating was used, a typical bandwidth of 9 GHz was achieved (in the KrF laser). At a locking efficiency of less than 50 percent, the tuning range was 1 nm. At the band maximum the locking efficiency was less than 5 percent. However, if an additional etalon was inserted, the bandwidth could be reduced to the astonishingly low value of 1.5 GHz. At the same time, the system delivers well over 100 mJ at the band maximum. Repetition rate could be pushed up to 250 Hz.

R. Dierking and colleagues (Institute for Quantum Optics, University of Hannover) presented the last interesting paper in the session on gas lasers. It dealt with the first successful experiments in the realization of a VUV anti-Stokes Raman laser based on atomic sulphur and selenium. Lines have been obtained at 148.7 nm and 167.5 nm, respectively. The starting level is always the 1S_0 state; this is populated by using the frequency-doubled or Raman-downshifted radiation of an F₂ (or an ArF) excimer to cause photo dissociation of COS (or COSe, respectively). The Raman excitation of the 1S_0 level was achieved in many experiments by using radiation from the same laser as was used for pumping the 1S_0 state. The

observed energies were in the μJ region, and the corresponding power output was in the kW range. The scientists believe that it will be straightforward to scale up these figures to the mJ and MW ranges. Further experiments will study the use of atomic oxygen in the same type of laser system.

Integrated Optics

J. Krauser (Specialized College of the German Post Office, Berlin) opened the deliberations with a very clear, almost tutorial presentation on the perspectives of monolithically integrated optics devices. He emphasized that, because of the absorption and dispersion characteristics of the currently popular glass fibers, fully integrated systems (optical, optoelectronic, and electronic elements on one chip) based on InP are the most promising ones. In particular, he emphasized the potential for commercial exploitation of InGaAsP quaternary materials. When challenged by a questioner, he said that the time frame in which fully integrated devices will become off-the-shelf items, will depend on private industry's interest which, in turn, must rest on cost considerations. On this basis, he expects that the first fully integrated, monolithic optoelectronic devices will appear on the market within 5 to 10 years.

In the second special review presentation of this session H. Heidrich (Heinrich Hertz Institute, Berlin) gave a careful analysis of polarization effects in integrated optical waveguide structures. Emphasizing that such effects have a crucial influence on the proper design of optical networks, he pointed out that, because of intrinsic TE-TM mode dispersion and other problems, the use of LiNbO_3 -based components does not permit the fabrication of polarization-independent devices (such as a directional coupler) in an acceptably reproducible manner. If, instead, InP is used, the fact that it has only a TE mode electro-optical effect causes other problems. Heidrich concluded his discussion by emphasizing the need for using polarization-preserving fibers.

The third talk in this session that I found arresting was presented by M. Kukartz (University of the Bundeswehr, Hamburg). He described investigations regarding the compression of short light pulses in glass fibers by self-phase-modulation. Self-phase-modulation, in conjunction with the dispersion of the group velocity, led to a linear chirp. This had been observed previously using visible-range light from dye lasers. Kukartz, however, used a phase-coupled Nd:YAG laser in CW operation, passing the infrared light through a monomode fiber and doing a spectral analysis of the output. Since at the YAG wavelength the group velocity dispersion is negligible, it was an unexpected result that, despite this, pulse compression was accompanied by a linear chirp. Up to 50-fold spectral broadening was observed. At sufficiently high input power levels, spectral asymmetry and the emergence of Raman light (at $1.12 \mu\text{m}$) was seen; this phenomenon clearly sets an upper limit for the usable power level.

Nonlinear Optical Processes

Quite surprising results were obtained in the experiment on 3rd order nonlinear susceptibilities of noble gases; these were reported by W. Leupacher (Physics Department, Regensburg). His research group measured the 3rd-order nonlinear hyperpolarizability γ_3 (i.e., the polarizability of a single atom) for He, Ne, Ar, Kr, and Xe. Their method was the study of nonresonant, and not phase-matched, 3rd-harmonic production of picosecond impulses. The light source was a phase-coupled Nd:Glass laser. The physical process is actually the 3-photon excitation of a virtual level just below an atomic energy state; i.e., the process $\omega_1 + \omega_1 + \omega_1 \rightarrow \omega_3$ (where ω_3 is the emitted harmonic). Values of γ_3 from $1.13 \times 10^{-64} \text{ cm}^4/\text{V}^3$ (for He) up to $2.12 \times 10^{-62} \text{ cm}^6/\text{V}^3$ (for Xe) were found. Leupacher pointed out that these values compare favorably not only with the electronic hyperpolarizabilities of gas molecules (like N_2), but also with those of liquids (for example, water with

$3.7 \times 10^{-63} \text{ cm}^4/\text{V}^3$), and even with such solids as quartz.

J. Wildenauer (Max Planck Institute for Quantum Optics, Garching) reported a new "record" achieved in that famous center: the production of the 9th, 11th, and 15th harmonics of the 1.312- μm radiation giant iodine vapor laser (the Asterix). The 9th and the 15th harmonics (at 146 and 87.7 nm, respectively), were produced by two KD*P crystals (to generate the 3rd harmonic) and then using the nonlinear interaction with noble gases (Ar, Xe, Ne). For the 15th harmonic (and the 11th), no gas-cell can be used (because of the very high frequency), so only a free stream of gas was employed for frequency multiplication. But the greatest "hit" was the production of the 11th harmonic (at 119.6 nm); the researchers did this in a single step, by a coherent transformation in Xe gas only. It must be noted that the transformation occurs at positive dispersion and, so far, has no theoretical explanation. The direct production of an 11th harmonic of any radiation is a worldwide "first." Incidentally, the Garching scientists also succeeded in producing directly the 9th harmonic. Current goals of research include the production of XUV radiation at 31 nm.

In the area of generating useable coherent high-frequency radiation, I heard one more interesting paper in this session. Presented by M. Röwekamp (Physics Group, Essen University), it dealt with the generation of tunable VUV radiation by stimulated Raman scattering in H_2 . Pumping was done by UV light from a dye laser, and in six anti-Stokes steps radiation at 193 nm was first generated. After amplification in KrF, this was fed into a second Raman cell and converted to 118-nm radiation.

Another set of talks concerned more sophisticated nonlinear effects. W. Blau reported on his work done with Irish colleagues while he was a visitor at the Physics Department of Trinity College, Dublin. These scientists studied, both theoretically and experimentally, degenerate four-wave interactions of picosecond pulses in organic molecules.

Using orthogonally polarized pump- and probe-beams, the thermally induced phase-grating could be eliminated, and in this way they could study the resonant 3rd-order electronic nonlinearities. They found that materials with long conjugate bond lengths (such as polydiacetylene and several infrared-absorbant dyes) have typical values of 10^{-11} esu for the 3rd-order susceptibility coefficient. Possible applications for optical signal- and image-processing have been pointed out.

T. Elsaesser (Physics Department, Technical University, Munich) talked about research regarding the nonlinear index of refraction of InSb at frequencies near the absorption edge. Using previously developed short-pulse methods, he observed self-defocusing and self-phase-modulation of ultrashort light pulses. These nonlinear effects are accompanied by a reduction of absorption, caused by the occupation of states in the conduction band of the semiconductor. Analysis of the results showed that for pulse energies around 10^{-6} J, the index of refraction suffers a relative change of 4×10^{-2} . The nonlinearity has a risetime less than 4 ps.

F. Forsmann and his colleagues (Institute for Applied Physics, Münster University) studied an interesting device, a silicon Fabry-Perot interferometer that carried integrated electrical contacts. Illuminating with the radiation from a Nd:YAG laser, an electro-optical self-interaction occurs which leads to unexpectedly high optical nonlinearity. Values of $10^{-4} \text{ cm}^2/\text{W}$ were produced for the nonlinear index of refraction. This led to optical bistability in the μW region, as well as to electric and optical multistability for only 300- μW switching power levels. The switching time was in the microsecond range. The authors developed a theoretical model based on a thermic process.

Novel Solid-State Lasers

Almost all talks in the two sessions on solid-state lasers reported on the development of devices with new laser hosts or doping materials. I will

report on those presentations which--for me at least--were most interesting.

B. Struve (Spindler & Hoyer, Göttingen) described studies with Cr- plus Nd-doped gadolinium-scandium-gallium garnets (GSGG), and also with Cr-doped gadolinium-scandium-aluminum garnets (GSAG). The Cr,Nd:GSGG emits at 1060 nm, and was found to have a 7 percent slope efficiency. It can have up to 20-W average power output. In single-shot operation the efficiency is 2 or 3 times larger than that of the Nd:YAG laser; at higher repetition rates thermal effects cause bad problems. The Cr:GSAG, emitting tunably around 780 nm, showed a slope efficiency of 0.4 percent (at 6-percent outcoupling level) and had a maximal output energy of 150 mJ per shot. Despite the fact that these figures are rather low and that thermal focusing also occurs here, the author found the Cr:GSAG devices most promising, reminding us that they are very new indeed.

In all these experiments rods up to 75 mm long and having a 6-mm diameter were used. Flashlamp discharge provided the pumping.

Struve's talk was supplemented by a colleague at his firm, P. Fuhrberg, who reported on Cr:GSGG and Cr:Perowskite (i.e., KZnF_3) lasers. These can be well tuned in the range of 750 to 850 nm and tuning is achieved with birefringent filters. They were optically pumped with Ar or Kr ion lasers. The slope efficiency was around 3 percent. Because the emission line is homogeneously broadened, efficient single-mode operation can be achieved. Experiments were made with several configurations. Particularly remarkable is that, for the first time, the researchers succeeded in constructing a single-mode solid-state ring-laser. Moreover, this was achieved without using frequency sensitive elements.

The crystals used in the Spindler & Hoyer experiments were supplied by Stuttgart University and the Institute for Applied Physics at the University of Hamburg. In fact, the latter institute, under the vigorous direction of Profes-

sor G. Huber, appears to be the foremost center in new solid-state laser research; it also has a substantial crystal growing capability. One paper from the Hamburg institute, read by J. Drube, reported on Xe-flashlamp-pumped Cr:GSAG and Cr:GSGG lasers, presenting complementary material to the two talks which I just reviewed. Two problems were encountered. First, it appears that thermal focusing leads to trouble even in each (single) shot (not only by accumulated effects in higher repetition rate operation). Second, the UV component in the Xe light leads to the formation of color centers, which compete with the Cr ion bands' absorption. Nevertheless, blocking out the UV from the pump light, 70-mJ output energy was achieved in the tunable range of 700 to 800 nm. Current work focuses on resonator optimization and better UV blocking. It may be interesting to note that some of the 2-inch rods were grown at the Lebedev Institute in Moscow.

The Hamburg Institute is doing work with many other, even less conventional laser materials. T. Wegner discussed experiments with a Cr-doped lanthanum-lutetium garnet ("Lalu-garnet" or just LLG) laser. With Kr laser optical pumping the group succeeded in producing quasi-continuous operation (2-ms pulse length) at room temperature. This was done in a concentric resonator configuration. When a free-running arrangement was used (820-nm radiation, 63-mW laser threshold), the slope efficiency was 17 percent, and the losses were 7 percent. With a prism, the laser could be tuned between 790 and 850 nm, the peak being at 820 nm.

Proceeding into more speculative areas, the third Hamburg paper, presented by R. Horn, reported on experiments with Cr-, Tm-, Ho-doped yttrium-scandium-aluminum garnets (YSAG) and yttrium-scandium-gallium garnets (YSGG). Optical pumping (with a Kr laser) was used. The most remarkable experiment demonstrated that successful CW-mode laser operation (with a pumping threshold of 25 mW and a slope efficiency of 13 percent) can be achieved (at room

temperature) by using the 5I_7 - 5I_8 transition in Ho. The wavelength was 2.086 μm . It is noteworthy that this infrared laser can be pumped (without undue heating losses) by purely visible light. The underlying processes of operation for these lasers are complicated. The Cr serves as a sensitizer; there is a good Cr-Tm transfer; and an almost loss-free cross-relaxation $\text{Tm}(^3F_4 \rightarrow ^3H_4)$ to $\text{Tm}(^3H_6 \rightarrow ^3H_4)$. Another system, Cr,Tm:YSGG was found to work at 1.862 μm . It could be pumped even by a flashlamp.

One more Hamburg contribution, read by C. Zimmermann, should be mentioned even though it reported a negative result. In this study Tb- and Sm-doped garnets were investigated because, should it work, such a laser would radiate in the much desired blue-green region. Spectroscopic studies showed that 30- to 40-percent amplification could be expected. Nevertheless, so far, laser action could not be achieved. This failure may be caused either by scattering losses or, worse, by the excited state absorption competing mechanism.

There was also a Hamburg talk on Ti-doped sapphire lasers, which are interesting because of the extreme tunability, from 680 to 1100 nm.

H. Li (Federal Research Institute for Technical Research, Braunschweig) gave an interesting report on progress at the institute with frequency-stabilized tunable CW laser operation of stoichiometric Nd crystals ($\text{LiNdP}_4\text{O}_{12}$, $\text{KNdP}_4\text{O}_{12}$, and $\text{NdP}_5\text{O}_{14}$). Lasing was obtained with diode-laser or Ar-laser pumping, and occurred at 1.05 or 1.32 μm . Tunability was a few percent. By injection locking of a laser diode, the 1.32- μm radiation could be amplified to mW outputs (420-dB amplification). Overall slope efficiency was 10 percent.

Surely the most amazing talk on novel solid-state lasers was presented by H. Nahme (Institute for Atomic and Solid-State Physics, Free University, Berlin). He recounted work with his colleagues in which they tested the possibility of producing lasers by freezing a sample of noble gas to a monocrystal between two plain mirrors--a most success-

ful attempt, I should say. Pumping with a 500-kV electron beam they achieved excimer densities of $5 \times 10^{17} \text{ cm}^{-3}$; this corresponds to a calculated overall amplification of 2 or 3 per cm. The experiments indeed showed laser radiation at 128 and 145 nm. 12-MW peak power was observed. Very strong fluctuations were found from crystal to crystal. It was ascertained that, even with the first shot, the crystal is usually destroyed (surprise, surprise!). Furthermore, it does not seem to be possible to produce lasing crystals with lengths of a centimeter or more; this would require excimer densities beyond reach.

3 SUMMARY

I think this meeting gave a fairly comprehensive overview of the most active fields in laser research and related topics as they are now pursued in West Germany. However, a cautioning remark is in order. Because of the meeting's inclusion in the Physical Society Convention, there must have been some prejudice, in the sense that almost all speakers were physicists from academic environments. Thus, engineers and private-enterprise research labs may not have had a valid representation.

I felt that the level of academic research was high, probably comparable to that in the UK, and that the researchers are up-to-date, serious, hard-driving colleagues. I was truly amazed by the high proportion of young (and very young) researchers among the speakers and the audience. I believe this is a good portent for the future.

I feel it to be my duty to report that the eruditeness, literacy, clarity of presentation, and self-assurance of the speakers (including graduate students) far surpassed anything I have seen for many years.

If the thematic choices of the program committee were unprejudiced (as I am sure they were) then it emerges that the most active subfield of quantum optics in German academia is research in the area of novel solid-state lasers. Next to it comes laser spectroscopy.

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